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Assessing the environmental impact of metal production processes

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Abstract

Evaluating both new and existing processes for primary metal production to assess their environmental impacts is often difficult due to the many inputs and outputs involved. Life Cycle Assessment (LCA) is a methodology that can be used for such purposes to identify those parts of the metal production life cycle that have significant environmental impacts. LCA has been used by CSIRO Minerals to assess the ‘‘cradle-to-gate’’ environmental impacts of a number of metal production processes practised either currently or potentially in Australia. The metals considered included copper, nickel, aluminium, lead, zinc, steel, stainless steel and titanium, by both pyrometallurgical and hydrometallurgical routes in some instances. The environmental profile included greenhouse and acid rain gas emissions, solid waste emissions and gross energy consumption. The results for various metals are compared in this paper. New process technologies for primary metal production can be expected to reduce the environmental impacts of metal production, and estimates of likely reductions for technologies involving stainless steel, titanium and aluminium are also presented in this paper.

Keywords: Sustainable development; Metal production; Environmental impacts; Life Cycle Assessment

1. Introduction

Sustainable development concepts have resulted in increasing environmental pressures to improve the efficiency of resource utilization and significantly reduce waste generation and emissions. These concerns have in turn focussed attention on the supply chains and life cycles in which minerals and energy resource processing take part, as resource processing represents particularly a critical stage for the potential release of gaseous, liquid and solid emissions, for it is here that chemical transformations often take place.

One way of achieving greater efficiency in resource use is by ‘‘dematerialisation’’, which is broadly defined as the reduction in the amount of energy and materials required to service economic functions (e.g. production of consumer goods or the provision of services). The closure of material loops through the re-use of materials complements the process of dematerialisation. While smaller and lighter products with longer service lives can reduce the amount of materials required by society, re-use and recycling can also minimise fresh inputs and waste outputs. Of the materials currently used by society, metals have the greatest potential for unlimited recycling. They are not biodegradable and their elemental nature means that they can have an unlimited lifespan. However, resources of minerals and metals are ‘‘non-renewable’’, hence their supply is finite.

The anticipated growth in the economies of the developing countries as they strive to improve their standard of living means that there will be an on-going need for primary metals well into the future, even with increased levels of dematerialisation and recycling. Even the achievement of ‘‘Factor 10’’ dematerialisation would still need a ‘‘maintenance’’ or ‘‘make-up’’ of primary metals, as thermodynamic constraints (i.e. a 100% conversion efficiency is physically impossible) and metal quality and product recovery issues will limit the extent to which dematerialisation and metal recycling will be possible.

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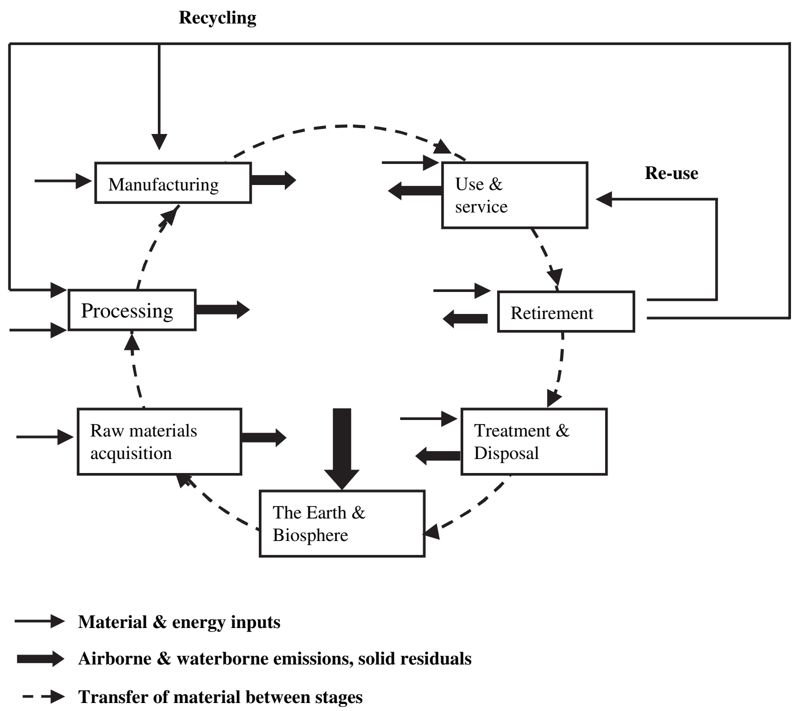

Fig. 1. The product life cycle system.

Given these concerns, it can be expected that operators of metal production processes will be increasingly required to reduce their environmental impacts. However, given the large number of feed streams, by-product streams, waste streams and energy inputs associated with resource extraction and processing, evaluation of new or existing metal production processes to achieve such goals is not always a straightforward exercise. To obtain a true environmental picture of a process, it is essential that the process be evaluated over its entire life cycle (see Fig. 1).

A number of environmental assessment tools and methodologies have been developed by the scientific community in recent years, and these include Environmental Impact Assessment (EIA), Ecological Risk Assessment (ERA), Material Flow Analysis (MFA), Materials Intensity per Unit of Service (MIPS), Cost Benefit Analysis (CBA) and Life Cycle Assessment (LCA) [1,2]. LCA is used to assess the potential environmental impacts associated with a product, process or activity during its entire life cycle, and is sometimes referred to as ‘‘cradle-to-grave’’ analysis. LCA methodology is being used by CSIRO Minerals [3–8] and others [2,9–11] to assess the environmental impacts of various metal production processes practised either currently or potentially in Australia. This paper compares the environmental impacts of these various metal production processes, examines issues that influence these impacts and discusses technology developments that may reduce these impacts.

2. Metal production processes

Various metal production processes included in the study are shown in Table 1. For some metals, alternative pyrometallurgical and hydrometallurgical processes were included. The reported amounts of these various metals produced in Australia [12] and the World [13] by these combined processes are given in Table 2.

Table 1
Metal production processes considered in the study

Metal	Feed	Process
Nickel	Sulphide ore (2.3% Ni)	Flash furnace smelting and Sherritt-Gordon refining
	Laterite ore (1.0% Ni)	Pressure acid leaching and solvent extraction/ electrowinning (SX/EW)
Copper	Sulphide ore (3.0% Cu)	Smelting/converting and electro-refining
	Sulphide ore (2.0% Cu)	Heap leaching and SX/EW
Lead	Sulphide ore (5.5% Pb, 8.6% Zn)	Lead blast furnace
	Sulphide ore (5.5% Pb, 8.6% Zn)	Imperial smelting process
Zinc	Sulphide ore (5.5% Pb, 8.6% Zn)	Electrolytic process
	Sulphide ore (5.5% Pb, 8.6% Zn)	Imperial smelting process
Aluminium	Bauxite ore (17.4% Al)	Bayer refining, Hall–Heroult smelting
Titanium	Ilmenite (36.0% Ti)	Becher and Kroll processes
Steel	Iron ore (64% Fe)	Integrated route (blast furnace (BF) and basic oxygen furnace (BOF))
Stainless steel	Pig iron (94% Fe), chromite ore (27.0% Cr, 17.4% Fe); laterite ore (2.4% Ni, 13.4% Fe)	Electric furnace and argon–oxygen decarburisation (AOD)

Table 2
Australian and World production of various metals (kt)

Metal	Australia	World
Nickel	124	1400
Copper	458	14,500
Lead	247	3150
Zinc	502	9100
Aluminium	1877	28,900
Titanium	–	78
Steel	9445	1,030,000

2.1. Copper

Copper is produced by both pyrometallurgical and hydrometallurgical processings [14] as shown schematically in Fig. 2, with further details shown in Table 1. Both processing routes were assessed using LCA methodology, with heap leaching being the process selected from the three hydrometallurgical processes as shown in Fig. 2, as this process is the more commonly used hydrometallurgical process with more data available in the literature.

2.2. Nickel

Nickel is also produced both pyrometallurgically and hydrometallurgically [15,16] as shown schematically in Fig. 3, with further details shown in Table 1. The pyrometallurgical and hydrometallurgical routes chosen from those shown in Fig. 3 were flash smelting and acid pressure leaching, as flash smelting is the major pyrometallurgical process while acid pressure leaching is becoming the most common hydrometallurgical route for laterite ores.

2.3. Lead and zinc

Lead and zinc are traditionally mined together, although the concentrates produced from these mixed ores are often processed separately to produce refined lead metal (the lead blast furnace process) and refined zinc metal (the electrolytic zinc process). However, both lead and zinc are produced by the Imperial Smelting process. All three processing routes [15] as shown in Fig. 4 were assessed using LCA methodology, and details are included in Table 1.

2.4. Aluminium

The two main processing stages for aluminium production are alumina refining (Bayer process [17]) and aluminium smelting (Hall–Heroult process [15]) as shown schematically in Fig. 5. The Hall–Heroult electrolytic process was adopted over a hundred years ago, and is the only process for aluminium production in commercial use today. Further details are given in Table 1.

2.5. Titanium

Current production of titanium is exclusively by the Kroll process [15], and the flowsheet of this process is shown schematically in Fig. 6, with further details in Table 1. In this process rutile (natural or synthetic) or titania slag is chlorinated to produce titanium tetrachloride ($TiCl_4$) which is then reduced with magnesium.

2.6. Steel and stainless steel

Steel production is generally subdivided into two main production routes: integrated (from iron ore) and electric (from

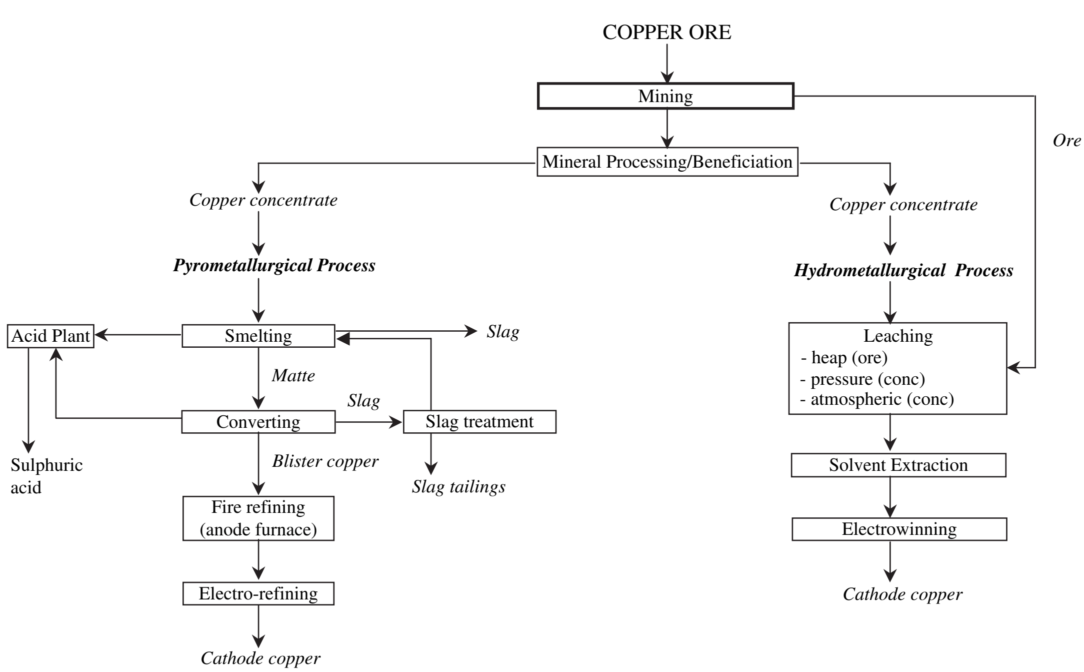

Fig. 2. Main processing routes for copper production.

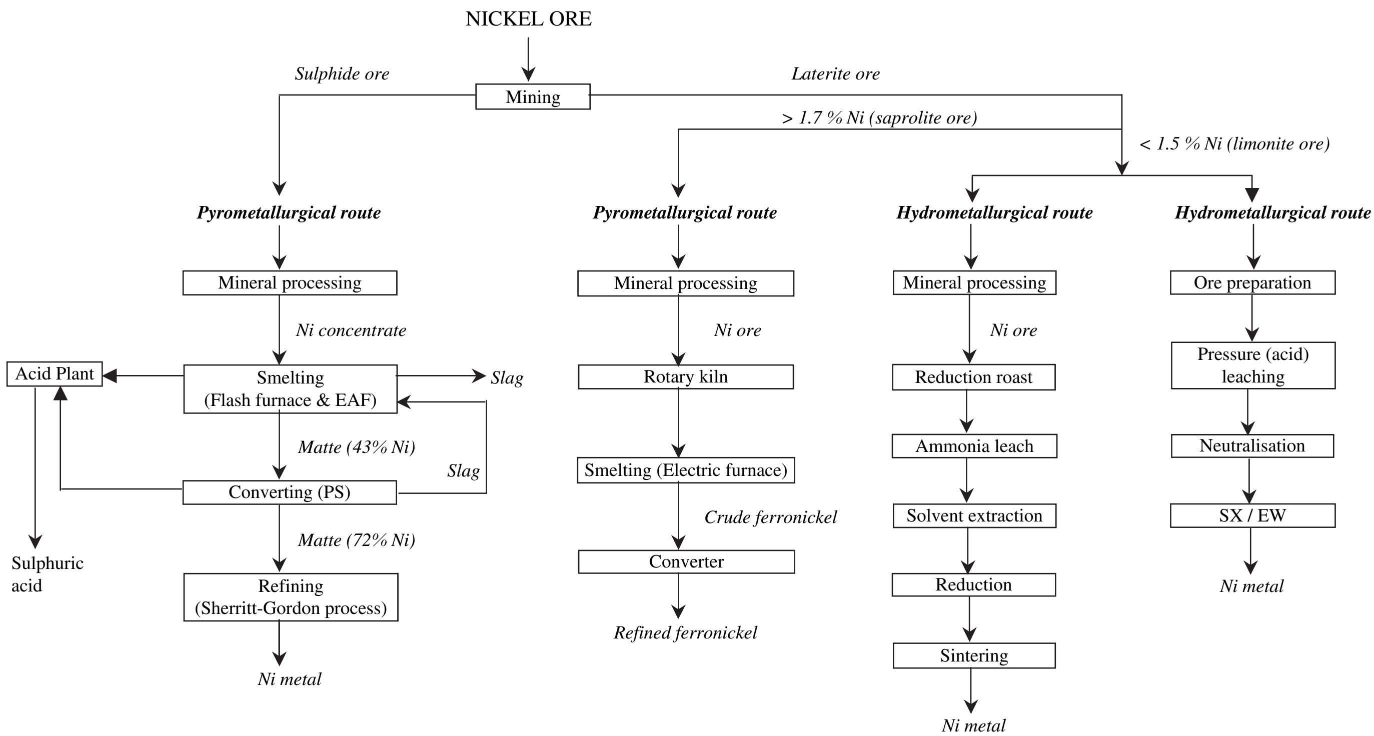

Fig. 3. Main processing routes for nickel production.

scrap) steelmaking [15]. A schematic flowsheet of the integrated route is shown in Fig. 7. Stainless steels are typically produced by a two-stage process [15]. Raw materials (including steel scrap) are melted together in an electric arc furnace, with the composition of the molten metal used corresponding approximately to that of the desired stainless steel product, apart from the carbon content. The molten metal is then transferred to a refining vessel (most commonly an argon–oxygen decarburization (AOD) vessel) which reduces the impurities (especially the carbon content) to the low levels required in the final product. A schematic flowsheet of stainless steel production by the electric furnace – argon/oxygen decarburization process is also shown in Fig. 7. Table 1 gives further details of the steel and stainless steel production routes considered.

3. Environmental impacts of metal production

The production of metals results in the formation of emissions – unwanted solids, liquids and gases – directly (during

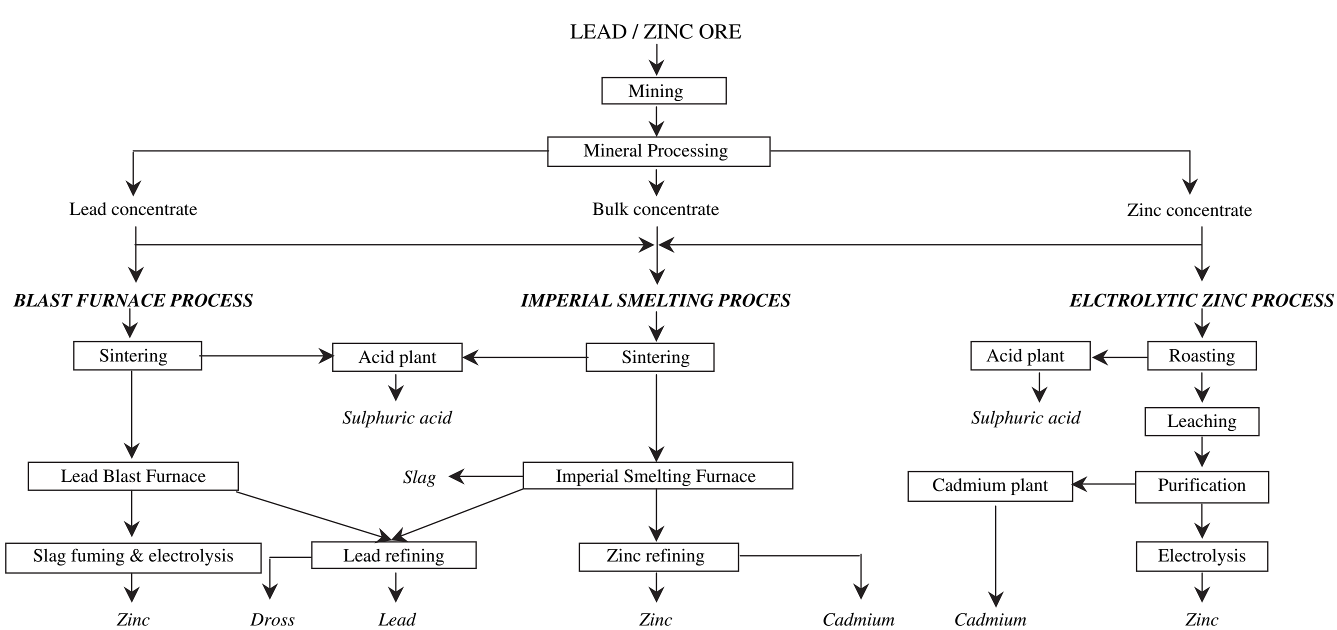

Fig. 4. Main processing routes for lead and zinc productions.

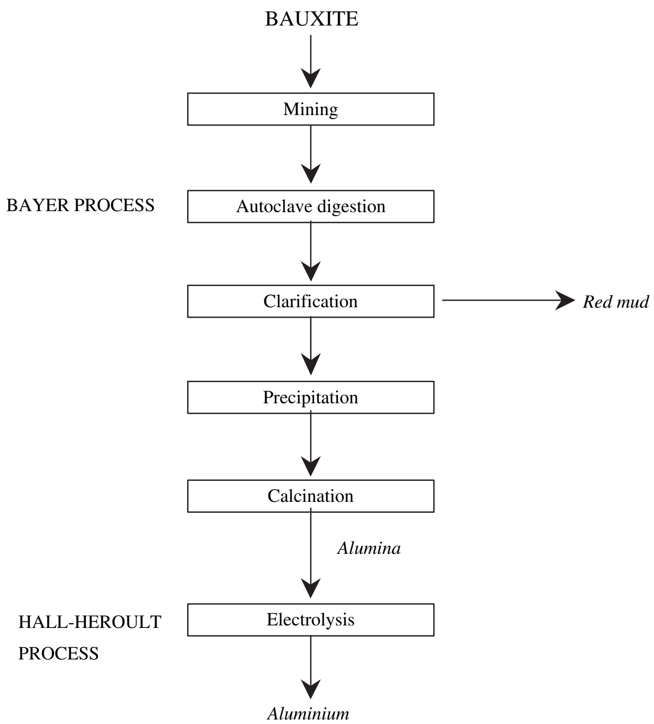

Fig. 5. Bayer and Hall–Heroult processes for aluminium production.

mining and processing) and indirectly (associated with the consumption of raw materials and utilities, e.g. in the generation of electric power and manufacture of reagents and explosives). As mentioned earlier, in the overall supply chain of material needs, mineral resource extraction and processing are particularly critical stages for the potential release of gas, liquid and solid emissions. Ores from mining are often physically beneficiated then chemically transformed to extract metals and produce industrial materials. This requires significant amounts of energy. The impacts are exacerbated by the use of reagents, water and fuel. There are toxicity concerns with a number of metals (e.g. cadmium, lead, and mercury) and even metals that are biologically essential may also become toxic at high levels (e.g. zinc and copper). The issue of metal toxicity is considered in more detail later.

4. Life Cycle Assessment

Life Cycle Assessment (LCA) methodology essentially involves the compilation of an inventory of relevant environmental exchanges during the life cycle of a product and evaluating the potential environmental impacts associated with those exchanges. The full product life cycle is usually divided into the following stages [18]:

- cradle to entry gate (raw material extraction and refining);
- entry gate to exit gate (product manufacture); and
- exit gate-to-grave (product use, recycling and disposal).

Based on impact assessment, two types of LCA can be distinguished, problem-oriented (mid points) or damage-oriented (end points). In the problem-oriented approach followed here, the environmental loads quantified in the inventory analysis were classified into the environmental impacts to which they contribute using appropriate equivalency factors. Some inventory items that represent flows to or from the system that cannot be assigned to any of the impact categories are often included in the LCA impact profile. Energy (input-related) and solid waste (output-related) are two such items [1,19]. The form of energy use included in LCAs is the Gross Energy Requirement (GER), also referred to as embodied energy or cumulative energy demand, which is the cumulative amount of primary energy consumed in all stages of a metal's production life cycle.

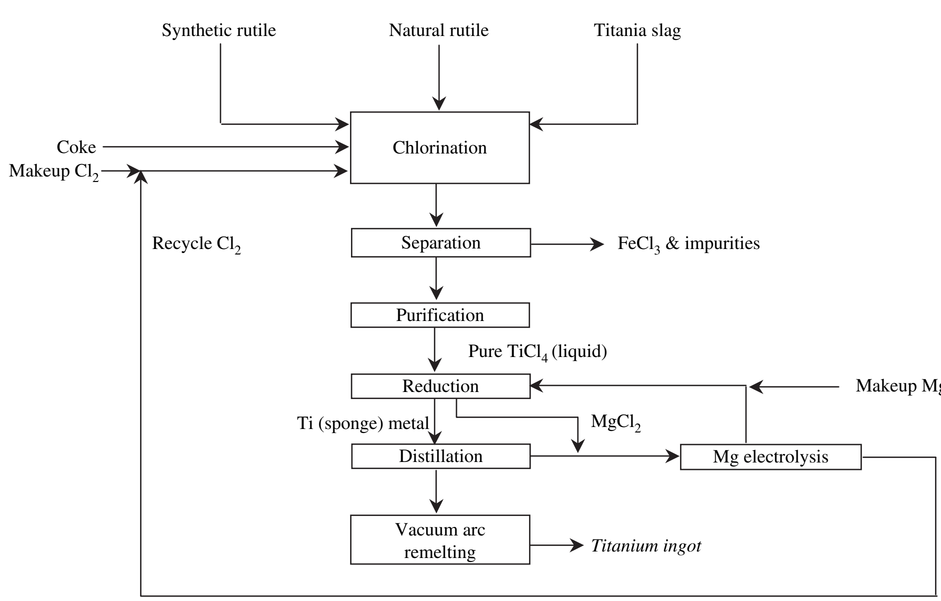

Fig. 6. Kroll process for titanium production.

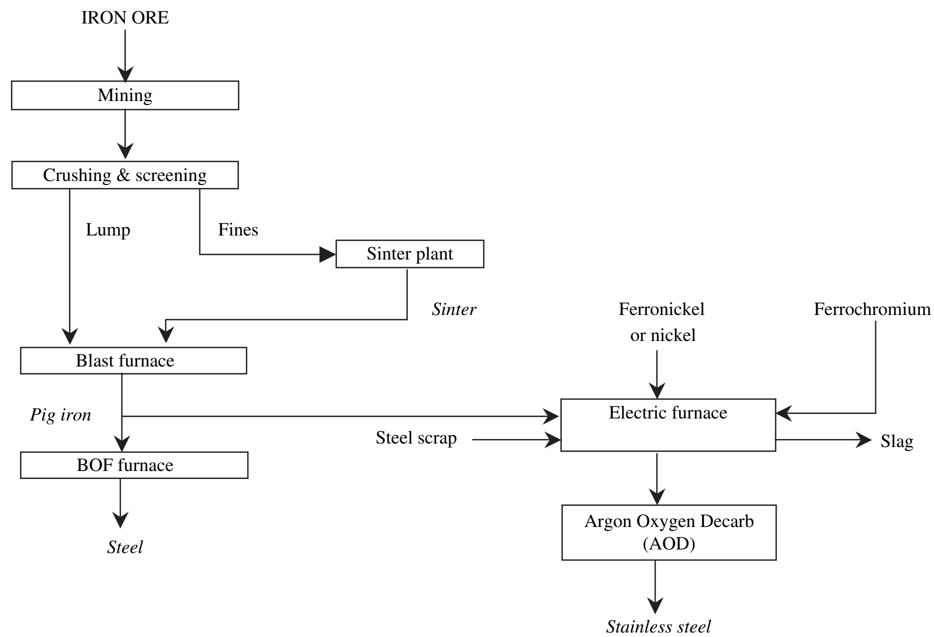

Fig. 7. Main processing routes for steel and stainless steel productions.

Individual "cradle-to-gate" LCA spreadsheet models of each of the metal production processes listed in Table 1 were set up, with each flowsheet being constructed at a level of detail consistent with processing data available in the literature. The inventory data used for each processing route were typical process data averaged over a number of sources where possible. This generally resulted in a flowsheet of three to five process steps, e.g. mining, mineral processing, smelting and refining. The environmental impact categories included in the LCAs were greenhouse and acidification gas emissions (i.e. Global Warming Potential [GWP] and Acidification Potential [AP], respectively), with the IPCC (Intergovernmental Panel on Climate Change) characterisation model being used to calculate these impact categories. While other environmental impact categories are also important, the data necessary to evaluate them are often not available in the literature. Furthermore, with regard to toxicity impact categories (human toxicity and eco-toxicity), LCA methodology assumes that all metals present in a solid waste will leach (mobilise) and enter into the environment. By using sequential leaching tests to characterise the mobility of metals in the solid waste from a hydrometallurgical copper process, Giurco et al. [2] showed that potential eco-toxicity and human toxicity impacts decreased by factors of 5.5 and 3, respectively, over results using the more conventional Toxicity Characteristic Leaching Procedure (TCLP). Basing toxicity characterisation on the mobile instead of total metal content would seem to be the most appropriate way of incorporating these toxicity impacts in LCAs involving waste solids from metal production processes [11]. As no such data for the processes considered were available in the literature, toxicity impacts have not been included in the LCAs at this stage.

The solid waste (including mining waste, tailings, slag and power station ash) burden (SWB) and GER were also included in the impact profile for each process. It was assumed that electric power was generated from black coal in all cases, at a generation efficiency of 35%. The inventory data and underlying assumptions used in setting up these spreadsheet models have been reported previously [3–8]. The study used the international standards' framework for conducting life cycle assessments contained in the ISO 14040 series [20].

While some of the metals considered here can be used interchangeably, others cannot. Therefore it could be argued that unit mass of refined metal is not the most appropriate functional unit for the latter metals. However, even for these metals, such information is useful, even if not for comparative purposes. For this reason, a functional unit of 1 kg of refined metal was used in the LCAs. For those processes where more than one metallic product is produced (e.g. lead, zinc and cadmium; Fig. 4), the environmental impacts were allocated to the metallic co-products on an equal weighting mass basis. No allocation of environmental impacts was made to any sulphuric acid produced (Figs. 2–4). Separate LCAs of ferronickel and ferrochromium productions were also carried out (but not reported here) to account for the environmental impacts of these alloying metals in stainless steel production.

5. Results

The "cradle-to-gate" results for GER, GWP and SWB for each metal production process considered are given in Table 3 and compared graphically in Figs. 8 and 9 for GER and GWP, respectively. The AP results are also given in Table 3. It can be seen from these results that the light metals, titanium and aluminium had the greatest "cradle-to-gate" environmental impacts in terms of GER, GWP and AP, followed by nickel. Steel and lead (by the blast furnace process) had the lowest "cradle-to-gate" environmental impacts in these terms. Nickel

Table 3
Environmental impacts for ‘‘cradle-to-gate’’ metal production

Metal	Process	GER (MJ/kg)	GWP (kg CO_2e/kg)	AP (kg SO_2e/kg)	SWB (kg/kg)
Nickel	Flash furnace smelting and Sherritt-Gordon refining	114	11.4	0.130	65
	Pressure acid leaching and SX/EW	194	16.1	–	351
Copper	Smelting/converting and electro-refining	33	3.3	0.040	64
	Heap leaching and SX/EW	64	6.2	–	125
Lead	Lead blast furnace	20	2.1	0.022	14.8
	Imperial smelting process	32	3.2	0.035	15.9
Zinc	Electrolytic process	48	4.6	0.055	29.3
	Imperial smelting process	36	3.3	0.036	15.4
Aluminium	Bayer refining, Hall–Heroult smelting	211	22.4	0.131	4.5
Titanium	Becher and Kroll processes	361	35.7	0.230	16.9
Steel	Integrated route (BF and BOF)	23	2.3	0.020	2.4
Stainless steel	Electric furnace and Argon–Oxygen decarburisation	75	6.8	0.051	6.4

and copper had the greatest environmental impact in terms of SWB, but this largely reflects the typical ore grades as shown in Table 1. This is discussed further later. Comparing the SWB results for copper and nickel hydrometallurgical processes in Table 3 indicates a much higher SWB for the latter process, even after accounting for the lower ore grade. This is due to the greater amount of mining waste associated with nickel laterite ores [21]. The hydrometallurgical processing routes for copper and nickel have greater environmental impacts in these terms, than the pyrometallurgical routes. Apart from differences in ore grade, this is largely due to the large amounts of electricity consumed in the electrowinning stage of these processes and the inefficiencies associated with the generation of this electricity.

However, as outlined earlier, the ‘‘cradle-to-gate’’ stage is only one part of the full life cycle of a metal or material in a particular application. The full life cycle environmental impact of any given metallic product can only be obtained by combining the ‘‘cradle-to-gate’’, gate-to-gate’’ and ‘‘gate-to-grave’’ impacts. Norgate et al. [8] illustrated this by performing some simple calculations that showed how the use of aluminium and magnesium to lightweight motor vehicles by replacing heavier steel components reduces the GER and GWP (see Fig. 10) over the lifespan of the vehicle, despite the higher ‘‘cradle-to-gate’’ GERs for aluminium and magnesium compared to steel.

6. Factors influencing environmental impacts

There are many factors or parameters associated with a particular metal production process that influence the ‘‘cradle-to-gate’’ environmental impacts of the process. These include ore grade, electricity energy source, fuel types, and material transport as well as process technology. Given the likely depletion of ore grades in the future, and the significant contribution that electricity generation makes to greenhouse gas emissions, the effect of the first two are considered in more detail below.

6.1. Ore grade

As higher grade reserves of metallic ores are progressively depleted, mined ore grades will gradually decrease. This reduction in grade will have a dramatic effect on the energy consumption and accompanying greenhouse and acid rain gas emissions from metal production processes. While the average grade of copper and nickel ores in Australia currently is relatively high (up to 3% and 2.3%, respectively – see Table 1), the potential effect of depleting ore grade is illustrated in

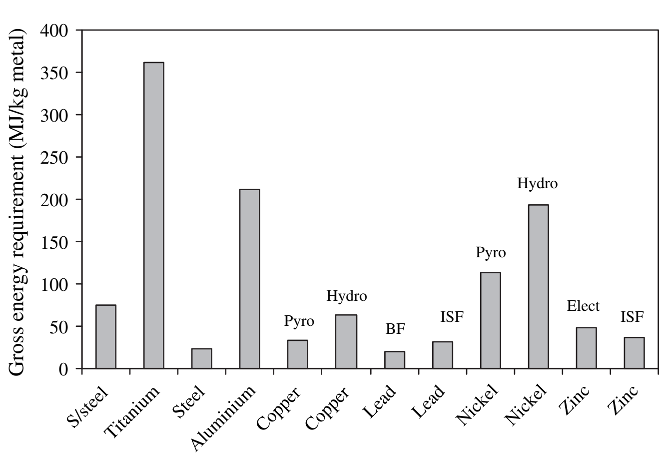

Fig. 8. GER for ‘‘cradle-to-gate’’ production of various metals.

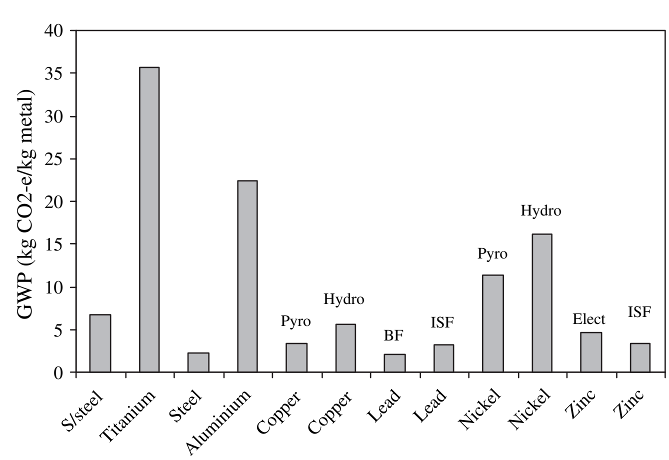

Fig. 9. GWP for ‘‘cradle-to-gate’’ production of various metals.

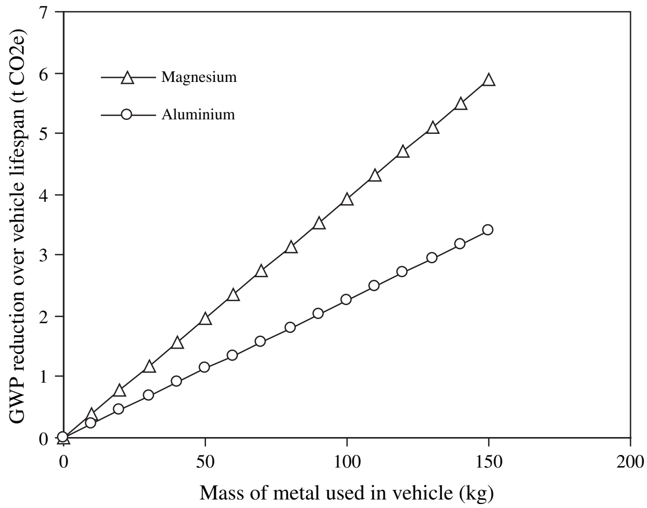

Fig. 10. Reduction in GWP from light weighting of motor vehicles.

Fig. 11 for copper production by the smelting and electrorefining route and nickel production by the smelting and Sherritt-Gordon refining route.

The impact of declining ore grade on GER as shown in Fig. 11 comes about largely because of the additional energy that must be consumed in the mining and mineral processing stages to move and treat the additional gangue material. Once a concentrate or mineral product of a specified grade has been produced, emissions from downstream processing (e.g. smelting and refining) are not significantly affected by the original ore grade. The effect of ore grade on the SWB is shown in Fig. 12 based on the data in Tables 1 and 3.

6.2. Electricity energy source

The energy source used to generate the electricity consumed in a particular metal production process also influences the "cradle-to-gate" environmental impact of that process. This may be illustrated by considering primary aluminium production [4]. The three main energy sources used for generating electrical power for aluminium production worldwide in 2003 were coal 36%, hydroelectricity 49% and natural gas 9% [22]. The effect of these three electricity energy sources on the GER and GWP for primary aluminium production is shown in Fig. 13. The generation efficiencies in the latter two cases were assumed to be best current efficiencies of 80% and 54%, respectively [4], compared to 35% for black coal.

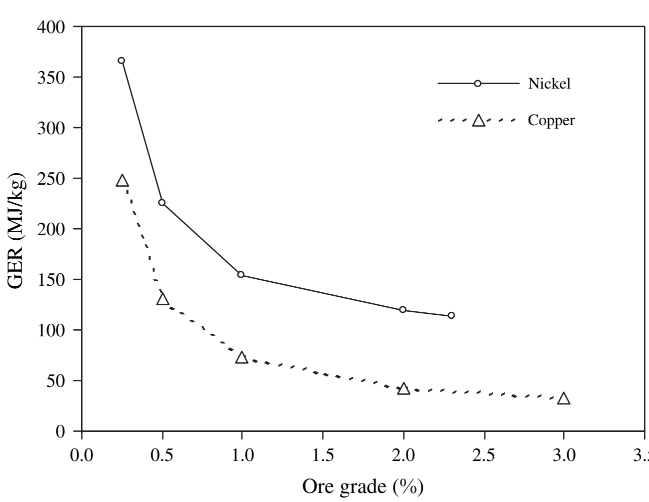

Fig. 11. Effect of ore grade on GER for copper and nickel productions.

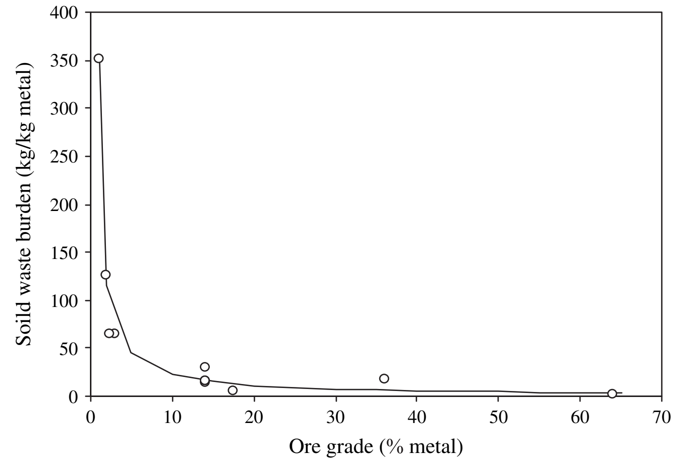

Fig. 12. Effect of ore grade on SWB for the production of various metals.

Two factors contribute to the effect shown in Fig. 13, greenhouse gas intensity of the energy source and electricity generation efficiency. Changing from black coal to natural gas at the same generation efficiency (35%) will reduce the GWP due to the lower greenhouse gas intensity of natural gas-based electricity compared to black coal-based electricity, viz. 0.57 t CO_2e/MWh and 0.96 t CO_2e/MWh, respectively [5]. However, this will not change the GER as the generation efficiency remains unchanged. Increasing the electricity generation efficiency to 54% and 80% for natural gas-based electricity and hydroelectricity, respectively, reduces both GER and GWP due to the reduction in primary energy consumed.

7. Technologies to reduce environmental impacts

A number of metal production technologies are currently being developed, both for existing processes and as alternative

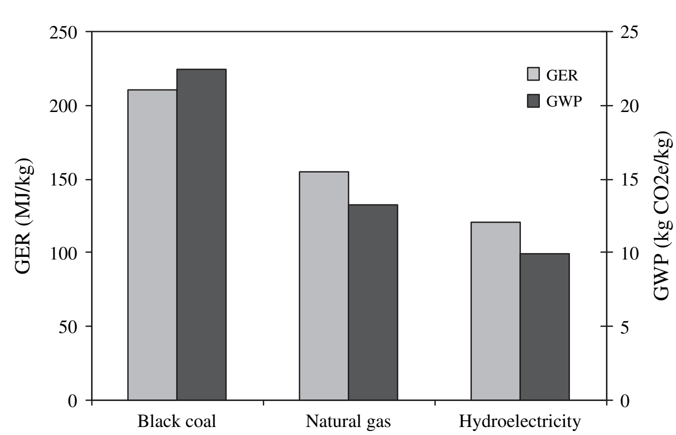

Fig. 13. Effect of electricity energy source on GER and GWP for aluminium.

processes, which are expected to reduce the environmental impacts of metal production. These potential reductions are discussed below for some of these technologies that are well advanced in their development and/or have strong possibilities of being commercialised.

7.1. Stainless steel production by bath smelting

A range of "direct smelting" processes using bath smelting technology have been developed in recent years to address many of the disadvantages associated with blast furnaces (e.g. agglomerated or lump feed, coke not coal, and coke ovens). In these processes, smelting takes place in a single reactor where ore and coal are both charged into the same melt or bath (hence the name "bath smelting"). The processes utilise post-combustion of the process offgases, the heat released being transferred back to the bath to compensate for the endothermic smelting reactions. One of the most advanced of these processes is the HIsmelt process for direct iron making which is being developed by Rio Tinto at Kwinana in Western Australia [23]. These bath smelting processes potentially offer significant savings in the GER for metal production processes currently carried out using electric furnaces (e.g. stainless steel and its feedstocks, ferronickel and ferrochromium), as the more direct use of thermal energy replaces electrical energy and its associated generation inefficiencies.

By assuming that a bath smelting process such as the HIsmelt process could be used for the production of ferronickel and ferrochromium (but still retaining the electric furnace for stainless steel), it was estimated [7] that the GER, GWP and AP for 304 stainless steel production could potentially be reduced by about 20–25% over the values for the conventional process as shown in Table 4. Furthermore, it is possible that direct smelting routes to stainless steel may offer opportunities to modify the chemistry of the slags produced to make them attractive as cement extenders, thereby reducing the SWB of stainless steel production.

7.2. Titanium production by the FFC Cambridge process

Endeavours to reduce the cost of titanium have seen a number of potential alternative production technologies reported in the literature in recent years. One of these processes is the FFC Cambridge electrowinning process [24,25]. In this process, TiO_2 powder is formed into an appropriately shaped cathode (incorporating a current collector) which then undergoes electrochemical deoxygenation in a cell containing calcium chloride electrolyte at a temperature of about 950 °C. One of the advantages claimed for the FFC Cambridge process is its ability to process a range of feedstock materials, however, at present, there is still significant uncertainty regarding the most appropriate TiO_2 feedstock to be used. Because of this, an additional feed preparation step was assumed necessary for this process.

Using small-scale data reported in the literature for this process, it was estimated [8] that the "cradle-to-gate" GER, GWP and AP for titanium production could potentially be reduced by about 10–15% over the values for the Kroll process as shown in Table 4. If the process can accept a lower TiO_2 purity feedstock as claimed (thereby eliminating the assumed feed preparation step), the GER, GWP and AP for the process would be reduced potentially by 30–35% as also shown in Table 4.

Table 4
Potential reductions in GER, GWP and AP with new technologies

Metal	Process	GER (MJ/kg)	GWP (kg CO_2e/kg)	AP (kg SO_2e/kg)
Aluminium	Hall–Heroult – conventional	211	22.4	0.131
	Hall–Heroult – VEC design	177	14.6	0.109
Titanium	Kroll	361	35.7	0.230
	FFC Cambridge	317	31.0	0.197
		239[a]	23.2[a]	0.152[a]
Stainless steel	Electric furnace and AOD	75	6.8	0.051
	Bath smelting	56	5.0	0.040

[a] If no feed preparation step required.

7.3. Vertical electrode cells for aluminium production

In conventional aluminium smelting involving electrolysis of alumina in Hall–Heroult cells, the carbon anodes participate in the cell reaction, while inert or non-consumable anodes are chemically and electrochemically non-reactive [26]. However, the expectation that inert anodes will increase the cell energy consumption over conventional technology has meant that inert anodes are being considered, in combination with drained (or non-wetted) cathodes and low temperature electrolytes, as the basis of a new cell design [27] referred to as the vertical electrode cell (VEC). The VEC configuration involves a multiplicity of electrodes suspended in the slurry electrolyte. The vertical electrodes alternate between being cathodes and anodes.

Energy savings for the VEC configuration over the conventional Hall–Heroult cell have been predicted to be in the order of 25–30% from a typical industry value of 15,000 kWh/t to about 11,000 kWh/t [27–29]. This cell arrangement is also expected to eliminate any perfluorocarbon (PFC) emissions from the cells by eliminating the brief upset conditions known as "anode effects". Based on this information, it was estimated that the use of vertical electrode cells could potentially reduce the GER and AP for aluminium production by about 15%, and the GWP by about 35% as shown in Table 4.

8. Future research

The ores mined for the production of metals, particularly base metals, contain trace levels of toxic/hazardous elements such as arsenic, mercury, cadmium, uranium, and thorium. While some of these minor elements are captured in the early stages of treatment of ores, the remainder gets dispersed through streams such as tailings, slags, fume and sometimes the product metal. It is thus reasonable to extend the scope of future LCA studies to include dispersion of these minor elements. Current knowledge on the magnitude of the minor elements, which are mined each year, is limited and insufficient for accounting for their dispersion. However, recently initiated research projects at CSIRO Minerals and the CRC for Sustainable Resource Processing are aimed at gathering the required data and predictive models for accounting for the dispersion of minor elements in various solid, liquid and gaseous streams.

9. Conclusions

Increasing dematerialisation will reduce the amount of metals required in most products. However, the growing demand for products, as under-developed countries increase their prosperity, will more than compensate for this. Thus these will continue to be an on-going demand for metals into the future, which will be supplied from a combination of primary metal produced from newly mined ores and recycled metals, although the amount of metal recycled will continue to increase.

Growing community concerns regarding waste generation and emissions can be expected to require the operators of metal production processes, along with others, to reduce their environmental impacts. However, the large number of feed streams, by-product streams, waste streams and energy inputs associated with most metal production processes means that the evaluation of both new and existing processes to achieve such goals is often difficult. Life Cycle Assessment methodology can be used in this situation to obtain a true environmental picture of a process over its entire life cycle, thereby identifying those parts of the metal production life cycle that have high environmental impacts.

While there are many factors or parameters that influence the "cradle-to-gate" environmental impacts of metal production processes, one of the most significant parameters is ore grade. As higher grade reserves of metallic ores are progressively depleted, mined ore grades will gradually decrease. This will result in an increase in the amount of gangue material that must be handled and disposed of, thereby increasing the environmental impacts of metal production.

Despite the "cradle-to-gate" environmental impacts for the production of light metals being substantially greater than those for many other metals, their "cradle-to-grave" impacts are less than these other metals in many applications in which their high strength-to-weight ratio is utilized. The use of light metals in such applications can be expected to increase in the future, although in applications where this special property is not critical, it is plausible that low energy-intensive metals such as steel may replace high energy-intensive metals such as aluminium.

New technology developments for both existing and alternative metal production processes can be expected to reduce the environmental impacts of metal production, a criterion that is increasingly being used to assess new technologies. These new technologies will be particularly important for the high energy-intensive metals such as aluminium and titanium.

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References

[1] Baumann H, Tillman A-M. The hitch hiker's guide to LCA. Lund, Sweden: Studentlitteratur; 2004.
[2] Giurco D, Stewart M, Petrie J. The role of LCA in performance assessment in minerals processing — a copper case study. Environmental issues and management of waste in energy and mineral production. 2000. p. 267—73.
[3] Norgate TE, Rankin WJ. Life cycle assessment of copper and nickel production. In: Proceedings of MINPREX 2000. Melbourne: The Australian Institute of Mining and Metallurgy; 2000. p. 133—8.
[4] Norgate TE, Rankin WJ. Greenhouse gas emissions from aluminium production — a life cycle approach. In: Proceedings of the international symposium on greenhouse gases in the metallurgical industries: policies, abatement and treatment. Toronto: Metallurgical Society of the Canadian Institute of Mining Metallurgy and Petroleum; 2001. p. 275—90. COM2001.
[5] Norgate TE, Rankin WJ. An environmental assessment of lead and zinc production processes. In: Green processing 2002. Cairns: The AusIMM; May 2002. p. 177—84.
[6] Norgate TE, Jahanshahi S, Rankin WJ. Alternative routes to stainless steel — a life cycle approach. In: Tenth international ferro alloys congress (INFACON X), Cape Town: South Africa; February 2004.
[7] Norgate TE, Jahanshahi S. Routes to stainless steel with improved energy efficiency. In: Green processing 2004. Fremantle: The AusIMM; May 2004. p. 97—103.
[8] Norgate TE, Rajakumar V, Trang S. Titanium and other light metals — technology pathways to sustainable development. In: Green processing 2004. Fremantle: The AusIMM; May 2004. p. 105—12.
[9] Giurco D, Stewart M, Petrie J. Decision making to support sustainability in the copper industry: technology selection. In: Sixth world congress of chemical engineering, Melbourne: Australia; September 2001.
[10] Lunt D, Zhuang Y, La Brooy S. Life cycle assessment of process options for copper production. In: Green processing 2002. Cairns: The AusIMM; May 2002. p. 185—93.
[11] Van Berkel R. Life cycle assessment for environmental improvement of minerals production. Minerals council of Australia environmental workshop; 2000. p. 484—97.
[12] Australian mineral statistics. December Quarter. ABARE; 2004.
[13] US Geological Survey. Mineral commodity summaries. US Geological Survey; January 2005.
[14] Biswas A, Davenport W. Extractive metallurgy of copper. 3rd ed. Pergamon; 1994.
[15] Habashi F, editor. Handbook of extractive metallurgy. Wiley-VCH; 1997.
[16] Kyle J. Pressure acid leaching of Australian nickel/cobalt laterites. In: Nickel '96. Kalgoorlie: The AusIMM; November 1996. p. 245—50.
[17] International aluminium institute website, <www.world-aluminium.org>.
[18] USEPA. Tools for the reduction and assessment of chemical and other environmental impacts (TRACI): user's guide and system documentation. USEPA; June 2003.
[19] Grant T, James K, Lunde S, Sonneveld K. LCA of paper and packaging waste management scenarios in Victoria. RMIT Center for Design; 2001.
[20] Environmental management — life cycle assessment — goal and scope definition and inventory analysis [AS/NZS ISO 14041:1999]. Standards Australia.
[21] Salinovich T, Strachan P. Nickel/cobalt laterites. ALTA Metallurgical Services; 1995.

[22] International aluminium institute statistical report, www.world-aluminium.org; 26 November 2004.
[23] Dry RJ, Bates CP, Price DP. Hismelt – competitive hot metal from ore fines and steel plant wastes. Dusseldorf: METEC Congress; 1999.
[24] Chen GZ, Fray DJ, Farthing TW. Direct electrochemical reduction of titanium dioxide to titanium in molten calcium chloride. Nature 2000; 407:361–4.
[25] Chen G, Fray D. Understanding the electro-reduction of metal oxides in molten salts. Light Metals 2004;881–6.
[26] Kvande H, Haupin W. Inert anodes for Al smelters: energy balances and environmental impact. Journal of Metals May 2001; 29–33.
[27] Brown C. Next generation vertical electrode cells. Journal of Metals May 2001;39–42.
[28] Beck T. Production of aluminium with low temperature fluoride melts. Light Metals 1994;417–23.
[29] Altdorfer J. DOE follows roadmap to Al technologies of the future. Journal of Metals November 2000;19–25.